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Effects of a chaparral-to-grass conversion on soil physical and hydrologic properties after four decades

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Abstract

Forty years after conversion from chaparral to perennial veldt grass in the San Dimas Experimental Forest, we compared land surface and soil properties between areas of the two vegetation types. Our objective was to evaluate the impact of this vegetation conversion on the soil physical properties likely to impact zero-order watershed hydrology. In three watersheds of each vegetation type, surface cover and soils were described within five watershed elements. Surface cover is approximately 90% in both vegetation types, but the frequency of individual plants is significantly higher in converted watersheds, leading to significantly lower variability in surface cover between grass watersheds. In chaparral watersheds, very fine to very coarse roots extend laterally and downwards in all directions. Only very fine roots emanate from grass, forming a dense fibrous mass that is concentrated below individual plants. In areas converted to grass vegetation, A-horizon bulk density is significantly higher due to the development of transitional AB-horizons that are absent from chaparral areas. Vertical changes between the surface soil and subsoil are more gradual under grass than under chaparral. The significantly higher frequency of grass plants caused concurrent transformation of much of the converted areas, removing the layered effect that is observed in the chaparral soils and allowing spatially homogeneous infiltration, distribution and storage of soil water.

Keywords: A-horizons; *Ehrharta calycina*; Pedogenesis; Water content; Surface cover; Wetting front

1. Introduction

Within a landscape, hydrology reflects the balance between independent factors of geology and climate and dependent factors including topography, soils and vegetation (Horton, 1932). These dependent factors are interrelated, and a sudden change in one causes adjustment by the others. On seemingly uniform slopes, hydrology is structured by interactions with vegetation and soil properties, affecting processes such as infiltration response and patterns of water penetration. The long-term, three-dimensional movement of water is, in turn, reflected by pedogenesis, as products of physical and chemical weathering are redistributed through the subsurface (Wagenet et al., 1994). Redistribution of water by the terrain has been

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correlated to spatial variability in A-horizon thickness (Moore et al., 1993), vegetation production (Demidov and Gorbenko, 1998) and organic matter accumulation (Stone et al., 1985). Accordingly, it is important to analyze soil characteristics within landform elements rather than isolated pedons (Slater et al., 1994).

Because soil physical and hydrologic properties are related to vegetation type, vegetation conversion can alter these properties. The physical structure of vegetation canopy and roots affects rainfall disposition by controlling how water is channeled into and through the soil (Himo et al., 1987; Martinez-Meza and Whitford, 1996; Specht, 1957). Vegetation type has been shown to alter soil hydrologic characteristics, including infiltration capacity, hydraulic conductivity and water retention (Gutierrez et al., 1995; Himo et al., 1987). Soil structure, organic matter content and nutrient concentrations are related to root distribution (Burke et al., 1987; Lee and Lauenroth, 1994; Martinez-Fernandez et al., 1995).

Vegetation conversion on the San Dimas Experimental Forest (SDEF) in southern California provides an opportunity to evaluate the decadal effects of vegetation change on soil characteristics. Analyses of the relations among vegetation type, water yield and erosion in the SDEF were undertaken in the 1950s and 1960s (Corbett and Green, 1965; Hopkins, 1958). Approximately 40 years later, the introduced vegetation persists in some watersheds adjacent to native chaparral watersheds. Our objective was to evaluate the impact of this vegetation conversion on the soil physical properties, bulk density and soil thickness, for example, related to regolith hydrology.

2. Materials and methods

2.1. Environmental setting

The SDEF is a 7000-ha area on the southern flank of the San Gabriel Mountains. It is representative of this part of southern California where dry-ravel (downward movement of dry sediment due to the steepness of slopes) equals or exceeds surface water-induced erosion (Kraebel and Sinclair, 1940; Wohlgemuth, 1985). Slopes in the area range up to 34° (76%), and bedrock, a mixture of highly weathered banded gneiss and granitics (Nourse, 1998), is generally encountered at < 60-cm depth. Typic Xerorthents are the predominant soil type (Ryan, 1991), but Typic Haploxeralfs are also common. The climate is Mediterranean with cool, wet winters and hot, dry summers. Temperatures range annually from about 38 to − 4 °C. Most precipitation falls as rain and annual precipitation varies from 292 to 1224 mm, with a mean of 678 mm (Dunn et al., 1988). The native vegetation is chaparral, an evergreen, summer-dormant vegetation community (Hanes, 1974). On the SDEF, this 1–3-m tall, dense canopy, sclerophyllous vegetation community includes chamise (*Adenostoma fasciculatum*), scrub oak (*Quercus dumosa*), hoaryleaf ceanothus (*Ceanothus crassifolius*), black sage (*Salvia mellifera*), bigberry manzanita (*Artcostaphylos glauca*), California buckwheat (*Eriogonum fasciculatum*) and yorbasanta (*Eriodictyon* spp.). Some chaparral species have roots >8 m deep, so plants can access water from deep within the soil and bedrock to survive long dry periods (Hill and Rice, 1963). All species reproduce after burning; some species resprout from root crowns and some germinate from seeds (Thomas and Davis, 1989).

After a fire in 1960 burned over 96% of the SDEF, large areas were rehabilitated using a combination of manual vegetation removal, herbicide application and seeding (Dunn et al., 1988) (Fig. 1). One such

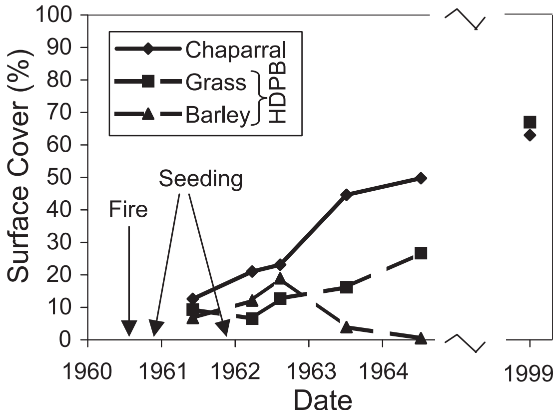

Fig. 1. Development of surface cover after the 1960 fire in watersheds with native chaparral vegetation and those that underwent the high-density perennial grass and barley (HDPB) hand-seeding treatment. Canopy surface cover was measured from 1961 to 1964 (Corbett and Green, 1965). Chaparral provided more cover in the 4 years immediately after the fire. The barley from the HDPB treatment did not return after the fourth year.

rehabilitation method involved high-density hand-seeding of perennial grasses in watersheds that were also stabilized by planting barley along contours in 0.6-m intervals (Corbett and Green, 1965; Rice et al., 1965). Perennial veldt grass (*Ehrharta calycina*) was only 15% of the original mixture, but is now the predominant vegetation in areas of this high-density perennial grasses and barley (HDPB) treatment.

Veldt grass, native to southern Africa, is adaptable to mountainous regions with sandy soils and a Mediterranean climate (Tothill, 1962). Veldt grass commonly occurs in association with other sclerophyllous vegetation types, including the heath of South Australia (Tothill, 1962). No quantitative data are currently available for veldt grass; however Specht (1957) observed that veldt grass has evapotranspiration approximately equal to that of heath vegetation. Veldt grass roots grow as deep as 2.4 m, and new roots grow at the surface after rain events (Tothill, 1962). As a result, veldt grass can survive long dry periods and prevent growth of other species in the spaces between individual plants (Tothill, 1962). Abundant seed dispersal and the ability to re-sprout from the root crown enable veldt grass to survive low-intensity fires (Smith et al., 1999).

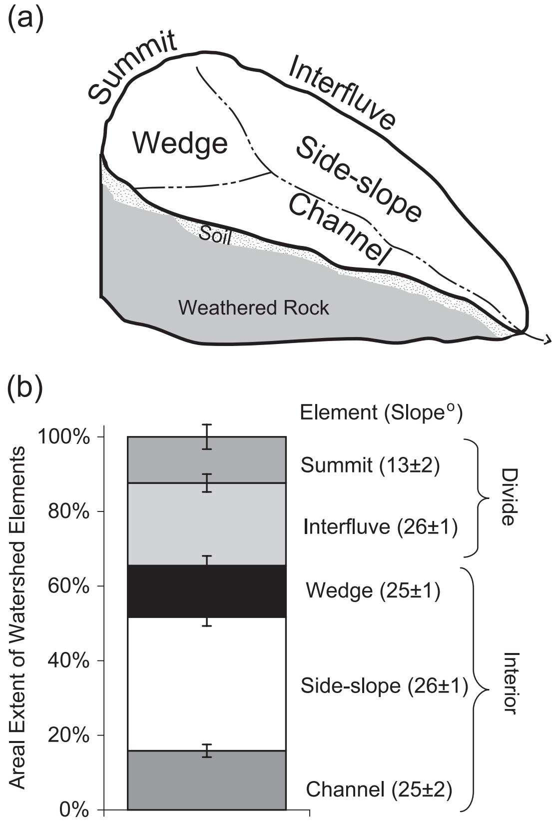

Fig. 2. (a) Schematic of a zero-order watershed. The five elements discussed in the text are shown. The boundary between the soil and weathered rock indicates the irregularity of this contact and that it does not always follow surface topography. (b) Areal extent and mean slope of each element averaged from all six watersheds used in the study. Watershed elements are discussed in the text as belonging to the divide or interior. The side-slope is the most areally extensive element. The summit is the element with the lowest slope gradient. Data are reported with bars to show standard error ($n=3$).

2.2. Field and lab methods

Zero-order watersheds, or hollows, in the SDEF drain into larger, first-order stream systems that are visible on a 1:24,000 map. Low-order drainages are important in quantitative analysis because of their similarity in different drainage systems (Horton, 1945). They provide a physical environment that integrates processes related to vegetation, pedogenesis and water movement. Six zero-order watersheds, ranging from 203 to 682 m^2, were selected; three with mixed chaparral vegetation and three with veldt grass. These watersheds range in elevation from 830 to 920 m, and all have easterly aspects.

Soil and underlying regolith were sampled, and characteristics were described as a function of watershed element. Sample locations were selected in the same relative element in each watershed. This strategy was chosen instead of random sampling so that relations among watershed elements could be compared between vegetation types. Five watershed elements were identified for analysis in each watershed (Fig. 2): (1) *channel*–in all cases, the channel is non-incised but distinct; (2) *side-slope*–connects the interfluve and channel; (3) *wedge*–a convex-planar, erosional feature connecting the summit and head of the channel ; (4) *interfluve*–the portion of the watershed divide that is parallel to the channel; (5) *summit*–the highest position in the watershed along the portion of the divide that is perpendicular to the channel. The side-slope is the most areally extensive watershed element and has an average slope representative of other interior watershed elements (Fig. 2). The summit represents a small portion of the watershed but is the area with the least slope gradient.

Surface cover was measured along randomly oriented 3-m line transects within each watershed element. Three chaparral and three grass watersheds were sampled, for a total of 45 m per vegetation type. Surface cover was designated as one of four categories: (1) stems/tussocks (a tussock is a clumped grass plant); (2) canopy; (3) litter; (4) gravel (mineral material $\geq$2-mm diameter). When multiple layers of cover (e.g., canopy over litter) were encountered, only the uppermost type was recorded. Transects were completed within a 2-day period during the winter (the time of maximum rainfall). Seasonal soil temperature was measured within the wedge element by burying NaCl diffusion cells at 50-cm depth (Trembour et al., 1988); temperature was averaged over 3-month periods (e.g., December 15–March 15).

One watershed of each vegetation type (termed the *focus watersheds*) was selected for more detailed study to link surface and subsurface soil properties with water movement. At each watershed element, one soil profile was described (Soil Survey Division Staff, 1993) and sampled by horizon for lab analyses. Data from Ulery et al. (1995) were used to estimate cation-exchange capacity and mineralogy of these soils for classification purposes. Carbon content of oven-dried, ground soil samples was measured by dry combustion using a Carlo Erba NA 1500 analyzer (Nelson and Sommers, 1986). Organic matter was removed with

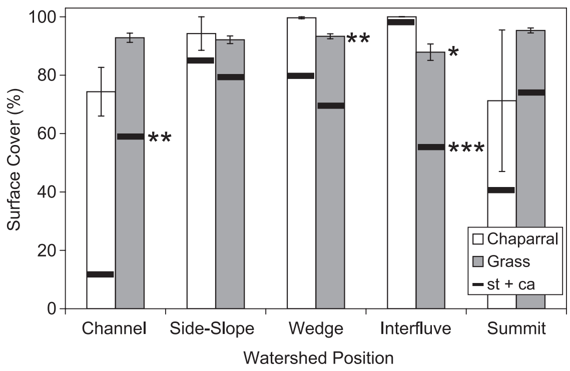

Fig. 3. Total surface cover by watershed element, including stems/tussocks, canopy, litter and mineral material $\geq$2 mm diameter. There is significantly more variability in total surface cover under chaparral. The cover provided by only stems/tussocks (st) plus canopy (ca) is shown by the position of the thick black lines. Grass interfluves have significantly less canopy cover than other grass watershed elements or chaparral interfluves. Level of significance of the difference between vegetation types is indicated by *, ** and *** ($p \leq 0.05$, 0.01 and 0.001, respectively). Cover was sampled along 3-m transects within each of the five watershed elements in each of the six watersheds. Data are reported with bars to show standard error.

30% hydrogen peroxide in preparation for particle size analysis by pipette (Gee and Bauder, 1986). Bulk density was obtained by the core method with samples dried at 100 °C (Blake and Hartge, 1986); core heights

Table 1
Physical environment created by vegetation, averaged over all watersheds[a]

Vegetation	Surface cover (%)				Roots[b] (number dm^{-2})			Soil Temperature[c] (°C)			
	Stems/ tussocks	Canopy	Litter	Total[d]	A-horizon	B-horizon	C-horizon	December–March	March–June	June–September	September–December
Chaparral	0.4 ± 0.2	63 ± 9	19 ± 5	88 ± 6	25–100 vf 1–2 f 0–1 m,c	5–100 vf 0–10 f 1–2 m 0–2 c 0–1 vc	0–30 vf 0–7 f 0–1 m,c	10.0 ± 0.5	13.9 ± 0.3	26.6 ± 0.4	20.0 ± 0.2
Grass	9 ± 2***	59 ± 2	25 ± 3	92 ± 1	25–200 vf	10–100 vf 0–1 f,m,c,vc[e]	0–100 vf	12.6 ± 0.5**	14.0 ± 0.2	24.1 ± 0.2***	21.8 ± 0.4**

, * Indicates a significant difference between vegetation types of $p \leq 0.01$ and 0.001, respectively.
[a] Surface cover and roots sampled in all watershed elements; soil temperature sampled within the wedge element.
[b] Root quantities are summarized from soil description data. vf: very fine (<1 mm diameter); f: fine (1 to $\leq$2 mm diameter); m: medium (2 to $\leq$5 mm diameter); c: coarse (5 to $\leq$10 mm diameter); vc: very coarse ($\geq$10 mm diameter).
[c] Temperature measured at 50-cm depth.
[d] Total includes cover provided by stems/tussocks, canopy, litter and mineral material >2 mm diameter.
[e] Only very fine roots emanate from grass plants; all coarser roots in grass watersheds are from other plant types.

Table 2
Soil descriptions for side-slope and summit elements

Horizon	Depth (cm)	Color[a]	Textural class[b]	Structure[c]	Clay films[d]	Roots[e] (number dm^{-2})
Chaparral side-slope—coarse-loamy, mixed, active, thermic Typic Haploxeralf						
O	1.5–0	7.5YR 2/0				Vf
A	0–3	10YR 4/6	sl	2vcpl → 2csbk → 1fsbk	n.o.	100vf
Bw	3–10	10YR 4/4	sl	1msbk → 1fsbk	n.o.	30vf < 10f 2m
Bt	10–26	10YR 4/6	sl	1fsbk	1n–pf	50vf 3f 1m 1c
Bt/Crt[f]	26–53	7.5YR 5/6	sl	2csbk/weathered bedrock	1n–rf 1n–co	20vf 5f 1m
Crt	53–107	7.5YR 5/8	sl	weathered bedrock	3k–br,rf	< 10vf 2f rf
Crt2	107–145	10YR 6/8	sl	weathered bedrock	3mk–br,rf	25vf 1f rf
Crt3	145–158 +	10YR 4/6	sl	weathered bedrock	3k–rf	1f < 10vf rf
2Crt	10–53	vldm	ls	weathered bedrock	3n–rf	25vf 2f rf
Chaparral summit—coarse-loamy, mixed, active, thermic Typic Haploxeralf						
O	1–0					
A	0–4	10YR 4/3	sl	3fpl	n.o.	100vf 1f 1m
Bt/[f]	4–53	10YR 5/4	l	2msbk	1n–co,br	30vf 1f 1m 1c
/2Crt[f]		vldm	sl	weathered bedrock	4mk–br,rf	25vf 4f 1m 1c
Crt	53–88	vldm	sl	weathered bedrock (1msbk)	2n–co	5vf
Crt2/[f]	88–118 +	vldm	ls	weathered bedrock (1msbk)	2n–co	10vf 1f 1m rf
/3Crt[f]		vldm	ls	weathered bedrock (1msbk)	3mk–rf	10vf
Grass side-slope—coarse-loamy, mixed, superactive, thermic Typic Haploxeralf						
O	3–0					vf
A	0–4	10YR 4/2	sl	2msbk	1n–co	≈ 200vf
AB	4–12	7.5YR 3/2	sl	1fsbk	1n–co	≈ 100vf
Bt	12–24	7.5YR 6/4	s	msbk	1mk–co 2n–co	≈ 100vfrf
2Bt/[f]	24–59	7.5YR 6/5	sl	2msbk	1n–br 1n–pf	≈ 30vf
/Crt[f]		vldm	sl	weathered bedrock	2mk–rf,co	≈ 100vfrf
E	59–61	10YR 7/6	sl	2msbk	v1n–co	n.o.

(continued on next page)

Table 2 (*continued*)

Horizon	Depth (cm)	Color[a]	Textural class[b]	Structure[c]	Clay films[d]	Roots[e] (number dm^{-2})
Grass side-slope—coarse-loamy, mixed, superactive, thermic Typic Haploxeralf						
Crt	61–92	vldm	s	weathered bedrock	3mk–rf	≈ 15vfrf
Crt2	92–110+	vldm	s	weathered bedrock	1n–co	n.o.
Grass summit—coarse-loamy, mixed, superactive, thermic Typic Argixeroll						
O	3–0					
A	0–4	7.5YR 3/3	sl	3cabk → 2fsbk	n.o.	≈ 200vf
AB	4–19	7.5YR 3/3	sl	2msbk	v1n–co,gr	≈ 100vf
Bt	19–45	7.5YR 3/3	sl	2csbk → 2msbk	v1n–co	≈ 50vf
					gr,cs	1f 1m
Crt	45–97	vldm	ls	weathered bedrock	3mk–co,rf	≈ 50vf
2BCrt	97–127	10YR 6/6	sl	2csbk → 2msbk	1n–co,pf	≈ 25vf
Crt2	127–130+	vldm	ls	weathered bedrock	2mk–co,rf	n.o.

[a] Color is for moist, crushed soil; vldm–variegated light and dark minerals.

[b] s—sand; ls—loamy sand; sl—sandy loam; l—loam; cl—clay loam.

[c] 1—weak, 2—moderate, 3—strong, f—fine, m—medium, c—coarse, vc—very coarse, pl—platy, sbk—subangular blocky, abk—angular blocky, → parting to, ()—soil structure observed in weathered bedrock.

[d] n.o.—none observed; v1—very few; 1—few; 2—common; 3—many; n—thin; mk—moderately thick; k—thick; gr—gravel; cs—coarse sand; co—colloid stains; rf—rock fractures; br—bridging grains; pf—ped faces.

[e] vf:very fine (< 1 mm diameter); f: fine (1 to ≤ 2 mm diameter); m: medium (2 to ≤ 5 mm diameter); c: coarse (5 to ≤ 10 mm diameter); vc: very coarse (≥ 10 mm diameter).

[f] Combination horizons; where possible, each portion of horizon described separately.

of either 6 or 3 cm were used as dictated by horizon thickness. Three replicates were sampled from each horizon. Saturated hydraulic conductivity (K_{sat}) was measured on intact soil cores using a constant head method (Klute and Dirksen, 1986); there was one core for each soil horizon. Field capacity (− 0.01 MPa) of the same intact soil cores was measured using Tempe cells, and wilting point water retention (− 1.5 MPa) was measured with disturbed soil material on pressure plates (Cassel and Nielsen, 1986; Klute, 1986); the difference is reported as plant-available water. Water repellence of air-dry, sieved soil material was measured using the water droplet test (King, 1981) in order to differentiate between soils with no, very low, low and moderate water repellence; data reported are averaged from four replicates from each surface horizon. Burrow frequency was measured at the surface and classified based on maximum diameter of the burrow; four classes were used (≤0.5, 0.5–2, 2–5 and >5 cm). Burrows were counted in a randomly oriented, 1-m^2 circular area within each watershed element (including both side-slopes) during the winter. A total of 18 m^2 was sampled in each vegetation type.

Infiltration capacity was measured within one side-slope and one summit element in the two focus watersheds. At each location, one measurement was made in a bare area, and one measurement was centered over a plant for a total of $n = 4$ for each vegetation type. A 20-cm-diameter single ring was pounded 5 cm into the soil and a constant 10-cm head of pressure was maintained (Bouwer, 1986). The rings for the side-slope were cut to 30° to approximate the surface slope angle so that the ring could be pounded into the soil vertically. The 10-cm head was maintained relative to the center of the ring. The water used for infiltration included FD and C Blue no. 1 (Brilliant Blue) food coloring (Flury and Fluhler, 1995).

The wetting front from the first large rain of the 1999 winter season (64 mm) was used to examine natural infiltration paths in the two focus watersheds. Antecedent water content in the upper 15 cm of soil averaged 2.0 ± 0.7% ($n = 6$) under chaparral and 0.8 ± 0.2% ($n = 8$) under grass. One pit in the side-slope element, measuring approximately 1 m wide by 0.5 m deep, was excavated parallel to the slope contour and water content was mapped on the pit face using a 5-cm grid (for a total of 69 chaparral and 86 grass measurements). Volumetric water content was measured in the field using a Trase time domain reflectometer (TDR, Soil Moisture, Santa Barbara, CA), and data were interpolated using Surfer (Golden Software). The depth of the measurements was determined by the ability of the TDR probe to be pushed into the regolith; consequently, there are more observations under grass.

In order to further examine surface soil differences between the two vegetation types and to allow for comparison among the five watershed elements, soils were described and sampled for bulk density in the other four zero-order watersheds used for the surface cover analyses. This provided replicates for each watershed element for bulk density and horizon thickness from a total of three watersheds per vegetation type.

Physical and hydrologic data were grouped by horizon (A and AB, Bw and Bt, and Crt) for comparison between the two vegetation types. For

Table 3
Selected laboratory data for side-slope and summit soils

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	C (%)	ρ_b[a] (Mg m^{-3})	Water retention (cm^3 cm^{-3})		Plant-available water (cm^3 cm^{-3})	K_{sat}[a] (cm min^{-1})
							FC[a]	WP[a]		
Chaparral side-slope										
A	0–3	64	23	13	14.4	n.d.	0.074[b]	0.023[b]	0.052[b]	n.d.
Bw	3–10	75	21	4	0.75	0.58	0.94	0.027	0.067	0.11
Bt	10–26	71	24	5	0.79	1.33	0.23	0.070	0.16	0.15
Bt/Crt[c]	26–53	71	24	5	0.33	1.52	0.20	0.089	0.11	0.14
Crt2	53–107	68	24	8	0.14	1.62	0.33	n.d.	n.d.	0.004
Crt3	107–145	69	27	4	0.09	1.65	0.19	0.078	0.11	0.25
Crt4	145–158 +	62	29	9	0.14	1.56	0.21	0.11	0.098	0.11
2Crt	10–53	82	15	3	0.20	1.64	0.10	0.049	0.056	0.2
Chaparral summit										
A	0–4	63	26	11	3.4	0.57	0.15	0.060	0.094	n.d.
Bt/[c]	4–53	52	32	16	0.56	1.39	0.27	0.16	0.11	0.26
/2Crt[c]		74	15	11	0.28	1.50	0.14	0.090	0.052	0.19
Crt	53–88	72	22	6	0.08	1.62	0.24	0.16	0.079	0.12
Crt2/[c]	88–118 +	77	17	6	0.06	1.73	0.21	0.17	0.045	0.053
/3Crt[c]		83	13	4	0.13	1.62	0.25	0.093	0.16	0.32
Grass side-slope										
A	0–4	77	17	6	2.7	1.24	0.16	0.11	0.051	2.18
AB	4–12	77	17	6	1.7	1.37	0.16	0.097	0.063	0.70
Bt	12–24	88	9	3	0.10	1.67	0.11	0.070	0.043	0.63
2Bt/Crt[c]	24–59	70	23	7	0.19	1.66	0.16	0.14	0.022	0.24
E	59–61	63	32	5	0.05	n.d.	n.d.	n.d.	n.d.	n.d.
Crt	61–92	88	9	3	0.04	1.86	0.10	0.084	0.015	1.40
Crt2	92–110 +	88	9	3	0.05	1.90	0.091	0.086	0.0044	3.08
Grass summit										
A	0–4	71	24	5	2.2	0.53	0.050	0.050	0.00046	n.d.
AB	4–19	72	22	6	1.6	1.14	0.16	0.083	0.082	1.31
Bt	19–45	73	22	5	0.91	1.29	0.19	0.076	0.12	1.11
Crt	45–97	81	16	3	0.11	1.59	0.16	0.063	0.095	7.28
2BCrt	97–127	66	26	8	0.18	1.66	0.22	0.076	0.14	2.06
Crt2	127–130 +	74	23	3	0.05	1.60	0.26	0.068	0.20	0.13

[a] ρ_b: bulk density, FC: field capacity (– 0.01 MPa), WP: wilting point (– 1.5 MPa), K_{sat}: saturated hydraulic conductivity.
[b] This horizon was too thin to sample for bulk density; water retention was estimated using an average bulk density value computed from the A horizons of the channel, interfluve and summit elements.
[c] Combination horizons; when possible, each portion of the soil horizon was described separately.

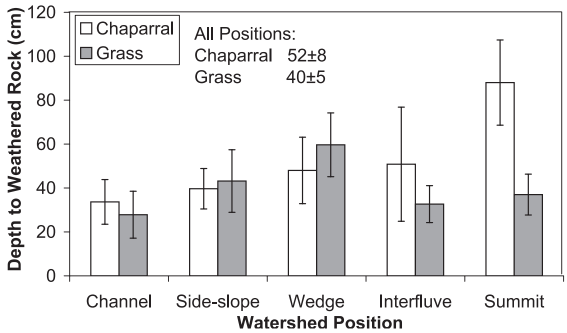

Fig. 4. Mean depth to weathered rock at each watershed element under chaparral and grass ($n = 3$). Data are reported with bars to show standard error. The summit is the only element where depth to weathered rock is differentiable ($p = 0.10$) between the two vegetation types. Mean depth to weathered rock for each vegetation type is also shown ($n = 15$).

statistical analyses, the watershed elements are the sampling units within the experimental unit of the watersheds; the treatment being evaluated is the presence or lack of vegetation conversion (Steel and Torrie, 1980). All data are reported with standard error, which is shown as error bars on graphs. Differences in means were tested using a two-tailed *t*-test for samples with unequal variance. Because of the differences observed in spatial variability between grass and chaparral soils, differences in variability between the two vegetation types were tested using a one-tailed *F*-test.

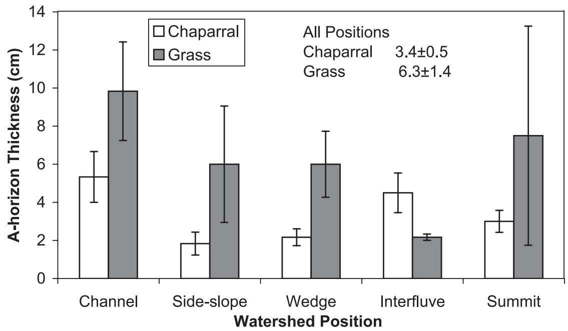

Fig. 5. Mean thickness of the A-horizon at each watershed element for chaparral and grass ($n = 3$). Data are reported with bars to show standard error. Mean A-horizon thickness for each vegetation type is also shown ($n = 15$). The difference between vegetation types has a $p = 0.06$ and an F-test showed that variability is significantly higher ($p < 0.001$) under grass.

Table 4
Mean values±standard error of bulk density (ρ_b) and hydrologic properties for chaparral and grass soils

	Chaparral					Grass				
Horizon†	ρ_b‡	Water retention		Plant-available	K_{sat}‡	ρ_b‡	Water retention		Plant-available	K_{sat}‡
	(Mg m^{-3})	FC‡	WP‡ (cm^3 cm^{-3})	water§	(cm min^{-1})	(Mg m^{-3})	FC‡	WP‡ (cm^3 cm^{-3})	water§	(cm min^{-1})
A	0.46±0.06¶	0.12±0.02	0.054±0.009	0.06±0.03	3.0¶	1.08±0.10***	0.16±0.02	0.09±0.008*	0.066±0.04	1.3±0.39
B	1.35±0.05···	0.223±0.01···	0.11±0.01··	0.12±0.04·	0.32±0.09	1.46±0.05··	0.18±0.03	0.090±0.01	0.092±0.06	0.94±0.45
C	1.66±0.02	0.22±0.02	0.12±0.003	0.094±0.06	0.22±0.06	1.71±0.04	0.15±0.03	0.086±0.02	0.061±0.06	1.6±0.70

*,*** Indicates significant difference ($p \leq 0.05$ and 0.001, respectively) between vegetation types.

·,··,··· Indicates significant difference ($p \leq 0.05$, 0.01 and 0.001, respectively) between A- and B-horizons under the same vegetation type.

† Mean values from all five watershed elements for A-, B- and C-horizons in one watershed of each vegetation type.

‡ ρ_b: bulk density, FC: field capacity (−0.01 MPa), WP: wilting point (−1.5 MPa), K_{sat}: saturated hydraulic conductivity.

§ Calculated by difference in retention at 0.01 and 1.5 MPa. Reported with pooled standard error.

¶ Due to the thin A-horizons under chaparral vegetation, K_{sat} was only analyzed for the wedge element; n=4 for ρ_b and $n \geq 5$ for all other values since data were grouped by horizon.

3. Results

3.1. Vegetation environment

There was an average of approximately 90% total surface cover in both chaparral and grass watersheds (Table 1). A layered cover, created by canopy over litter, is common in both vegetation types. However, a difference in the distribution of cover is evidenced by the significantly higher variability ($p<0.001$) in cover under chaparral, relative to grass (Table 1 and Fig. 3). The most significant contrast is how the cover is related to individual plants (st + ca in Fig. 3). In chaparral watersheds, < 1% of the area was covered by plant stems. In grass watersheds, 9% of the surface was covered by the base of grass tussocks that had diameters of up to 30 cm (Table 1), indicating the permanence of these perennial grass plants. Soil temperature in converted watersheds was significantly warmer ($p<0.01$) from September to March and significantly cooler ($p<0.001$) from June to September (Table 1).

Surface cover characteristics are reflected in the subsurface, where the distribution of plant roots is different between the two vegetation types (Tables 1 and 2). In chaparral watersheds, very fine to very coarse roots are distributed laterally and vertically, with very fine roots extending to ≥ 161-cm depth. Only very fine roots emanate from grass plants, with roots extending to ≥ 127-cm depth. The grass roots extend directly below the tussocks, forming a dense, fibrous mass near the surface that coincides with areas of dark soil. Occasionally, fine or coarser roots were observed in grass watersheds when invading shrubs were present.

Table 5
Water repellence under each vegetation type[a]

Vegetation[b]	Watershed element				
	Channel	Side-slope	Wedge	Interfluve	Summit
Chaparral	moderate	moderate	low	none	none
Grass	moderate	moderate	moderate	moderate	very low

[a] None, very low, low and moderate water repellence based on water droplet entry times of < 1, 1–7, 8–84 and 85–240 s, respectively (King, 1981).

[b] Sampled from one watershed of each vegetation type ($n=4$ for each surface horizon).

Table 6
Infiltration capacity at side-slope and summit elements[a]

Vegetation	Infiltration Capacity				
	Bare Area ($cm\ min^{-1}$)		Over plant ($cm\ min^{-1}$)		Average ($cm\ min^{-1}$)
	Side-slope	Summit	Side-slope	Summit	
Chaparral	2.8	1.8	1.6	1.2	1.9 ± 0.3
Grass	1.7	4.4	1.5	1.3	2.2 ± 0.6

[a] Infiltration capacity was measured within the side-slope and summit elements in the two primary watersheds. At each location, one measurement was made in a bare area, and one measurement was centered over a plant for a total of $n=4$ for each vegetation type.

3.2. Regolith physical properties

Soil descriptions (Table 2) and laboratory data (Table 3) are shown for the side-slope and summit elements for one watershed of each vegetation type. These examples are representative of soils at other watershed elements and in other watersheds. Weathered bedrock underlies the soil throughout the SDEF, and roots of both vegetation types extend into the weathered bedrock (Cr horizons in Table 2). Thin to thick clay films are common in the weathered bedrock. Black stains are present, and strong effervescence with 30% H_2O_2 confirmed the presence of manganese oxides. Multiple weathered bedrock horizons, and sometimes multiple parent materials, were described for each soil profile. Local heterogeneity due to foliations, fractures and igneous intrusions is common in this mixture of granitic and gneissic lithologies. These lithologic heterogeneities cause no significant difference in the textural class of the weathered bedrock among the watersheds (Tables 2 and 3). Mean depth to weathered bedrock (Fig. 4) shows the largest difference between vegetation types at the summit element, the only position where depth to weathered bedrock is distinguishable between grass and chaparral ($p=0.10$).

In general, grass A-horizons are thicker than those under chaparral ($p=0.06$; Fig. 5). For the interior watershed elements (the channel, side-slope and wedge), there is indication that grass A-horizons are thicker than those under chaparral, while at the interfluve, the A-horizon is thinner under grass relative to chaparral. Regardless of watershed element, the A-horizon is thickest below individual grass tussocks.

Soil descriptions from summit and side-slope elements provide examples of other pedomorphic differences between the two vegetation types (Table 2). The range in A-horizon soil color is larger in grass, relative to chaparral, areas. The value/chroma of A-horizons under chaparral ranges from 4:3 to 4:6. In grass watersheds, the value of A-horizons ranges from 3 to 5 and the chroma from 2 to 4. Total organic carbon (kg m^{-2}) in the upper 6 cm of soil (the mean A-horizon thickness) is not significantly different between chaparral (137 ± 31) and grass (172 ± 41).

3.3. Regolith hydrologic properties

Mean soil bulk density was compared for A-, B- and C-horizons using data from all six watersheds. The bulk density of A-horizons is significantly lower

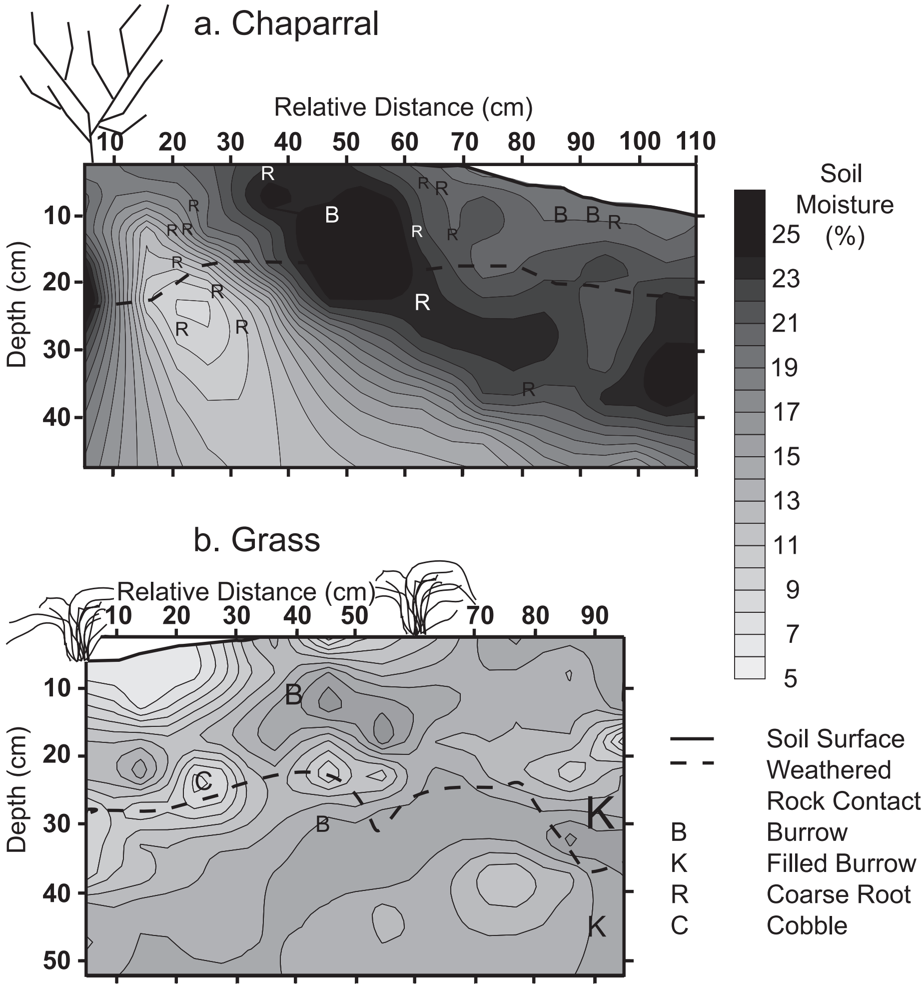

Fig. 6. The wetting front from the January 25–26, 1999 storm (64 mm of rain) was mapped within the side-slope element under chaparral (a) and grass (b). Before this event, there had been 0.5 mm of rain in the previous 37 days. Volumetric water content (%), shown as shaded contours, was measured in the field after the storm. Soil and weathered rock were moist under both vegetation types; however, there was a smaller range in water content under grass. Water content was measured in a 5-cm grid on a pit face. The upper boundary of the sampling grid was aligned with much of the soil surface. Places where the surface and upper boundary of the sampling grid do not coincide indicate surface depressions. The nearest plant(s) is shown for each pit. Locations of burrows, coarse roots and cobbles exposed in the pit face are noted; there is no consistent relation between these features and highs or lows in water content. The size of the letter corresponds to the size of the feature.

than that for B-horizons under both chaparral ($p<0.001$) and grass ($p<0.01$). The mean A-horizon bulk density is significantly higher ($p<0.001$) under grass compared to chaparral (Table 4).

Mean soil water retention and K_{sat} values were compared for A-, B- and C-horizons using data from one watershed of each vegetation type (Table 4). There are no significant differences in plant-available water retention, the difference in water available between -1.5 and -0.01 MPa ("wilting point" and "field capacity", respectively), between soils under chaparral and grass. However, average water retention of grass A-horizons at -1.5 MPa is significantly ($p<0.05$) higher than that of chaparral A-horizons. Chaparral A-horizons retain significantly less ($p<0.05$) water than underlying horizons at all conditions measured. Under grass, both water retention and K_{sat} are similar throughout the profile.

Water repellence is a soil hydrologic characteristic commonly associated with chaparral vegetation (DeBano, 1974) and is an example of a hydrologic parameter that is spatially discontinuous (Gutierrez et al., 1995; Imeson et al., 1992). The water droplet test showed that soils from both vegetation types exhibit water repellence (Table 5). Accordingly, infiltration was evaluated using both ponded and natural rain-event conditions. Infiltration capacity was measured at the summit and side-slope in the open spaces between plants and over individual plants. The average infiltration rate across both vegetation types ($n=8$) was 2.04 ± 0.38 cm min^{-1}; there was no difference between vegetation types (Table 6). Dye, applied as part of the ponded infiltration, showed no conclusive information regarding flow paths into the soil. Some dye was observed along insect and animal burrows, but an analysis of burrow frequency and size showed no measurable difference between chaparral (3.9 ± 1.1 burrows m^{-2}) and grass (2.1 ± 0.5 burrows m^{-2}) watersheds.

The wetting front from the January 25–26, 1999 storm showed differences in how water moves into and through the soil under chaparral and grass. This was the first rain event (>0.5 mm) in 37 days (Larson, 1999), so volumetric water content was low (2.0 ± 0.7% under chaparral and 0.8 ± 0.2% under grass) before the storm. A total of 64 mm of precipitation fell in 45 h. The wetting front was described 2 days after it rained. Under chaparral, a nonuniform wetting front was observed (Fig. 6a), with an 18% difference in water content within a distance of 30 cm. Total water content in the upper 50 cm of regolith averaged 65.1 ± 6.1 mm across the length of the pit face (approximately 1 m), similar to the precipitation amount of 64 mm. An area of low water content coincided with roots from a buckwheat plant that was 10 cm upslope from the left corner of the pit face. A linear path of relatively high water content to below 50 cm (the depth sampled) towards the lower right followed the local bedrock structure that dips to the north (the lower right side of the pit, Fig. 6a). Under grass, the wetting front was >80 cm deep (Fig. 6b). Measured water content ranged from 6% to 17%, two-thirds of the range present under chaparral. Within the soil (the upper 20 cm), the average water content under grass (12.6 ± 0.6%) was significantly less ($p<0.001$) than that under chaparral (20.9 ± 0.5%). Total water content in the upper 50 cm of regolith averaged 53.8 ± 2.6 mm across the length of the pit face, less than that present under chaparral ($p=0.06$). One grass plant was located at the left corner of the pit, and a second plant was located 60 cm to the right. The weathered bedrock in this pit was massive, with no obvious joints or foliations. The weathered bedrock below 45-cm depth was moist, but too hard to allow insertion of the TDR probe.

4. Discussion

Four years after the 1960 fire, chaparral provided 50% surface cover and grass cover in HDPB areas had reached 25% (Corbett and Green, 1965). Chaparral stands at this elevation (600–900 m) achieve approximately 100% surface cover by 22 years (Hanes, 1971). Both vegetation types provided almost complete cover in 1999, but the distribution of this cover was significantly altered in watersheds converted to grass (Table 1 and Fig. 3). The frequency of chaparral stems and grass tussocks is the greatest contrast in surface cover between the two areas (Fig. 7). In chaparral watersheds, surface cover is provided by the dense, interlocking canopy of different species, but plant stems are commonly separated by >3 m. In grass areas, the dominance of a single species and high frequency of plants

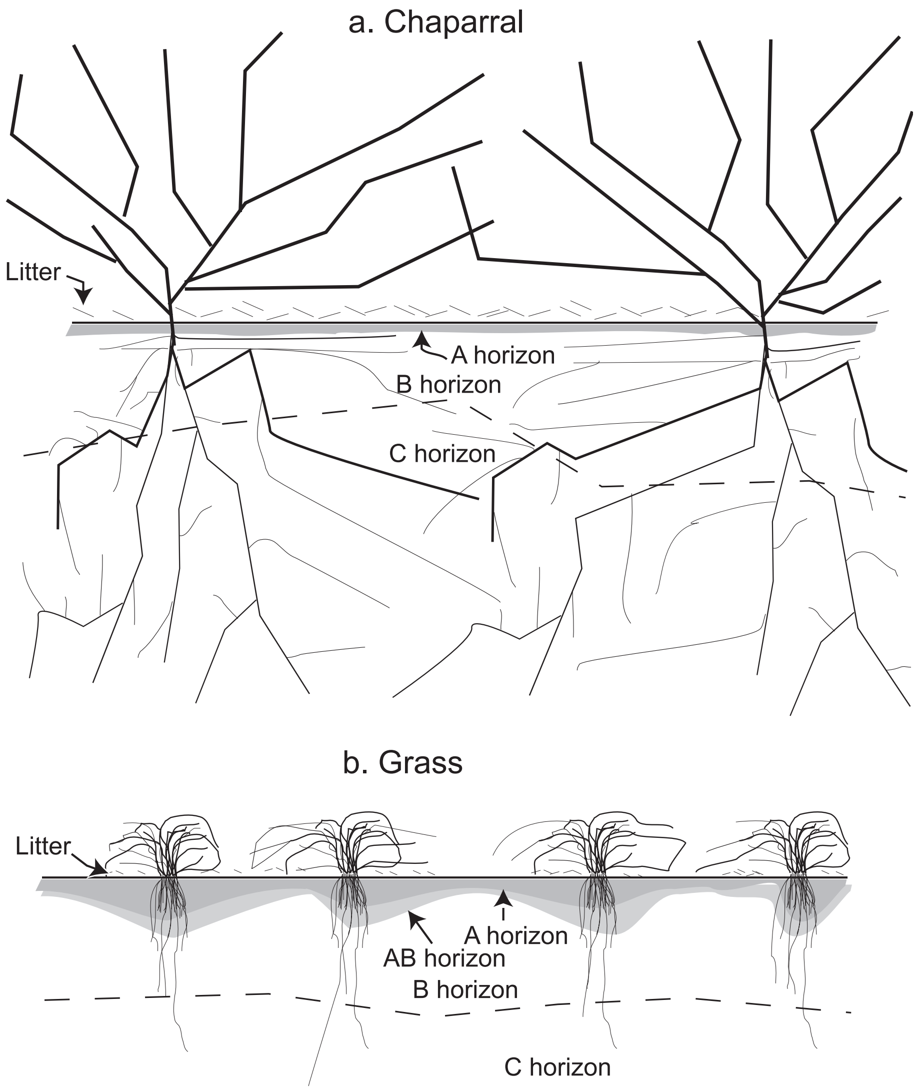

Fig. 7. Schematic of the relation between plants and soils in the two vegetation types. Horizontal field of view is approximately 3 m; vertical dimension not to scale. In chaparral areas (a), plant frequency is low, but the interlocking canopy covers most of the surface. Most organic matter comes from the extensive canopy, preventing a concentration of organic litter near shrub stems. Chaparral roots extend laterally and downward from the shrub stem, reflecting the expanse of the canopy. Consequently, lateral variability in A-horizon properties is low because roots and litter are not concentrated around plant stems. Under grass (b), the canopy, litter and roots are all concentrated around individual plants, resulting in an accumulation of organic matter in the soil below each plant and producing a laterally variable A-horizon. This accumulation of organic matter to varying depths under grass results in the development of transitional AB-horizons and a gradual change from the surface to the subsoil.

suggest a relatively uniform cover and, consequently, uniform disposition of rainfall. Both chaparral and grass canopies intercept rainfall, some of which is ultimately transmitted as stemflow (Beard, 1962; Clark, 1940; Corbett and Crouse, 1968; Hamilton and Rowe, 1949; Rowe and Colman, 1951). Consequently, the lateral homogeneity of infiltration under grass should be increased relative to chaparral areas simply due to the higher frequency of individual plants.

Differences in water movement created by vegetation surface cover are complemented by the distribution of roots in the subsurface (Table 2 and Figs. 6 and 7). Nonuniform flow of water into the soil under chaparral is compounded by the spatially heterogeneous distribution of roots that nonuniformly access water from the soil and weathered bedrock. Homogeneous water delivery at the surface in grass watersheds is maintained by the fibrous root mass emanating from each tussock. Lateral uniformity in water delivery and subsurface distribution probably increased as a result of the vegetation conversion. Both chaparral and grass roots extend into the weathered rock. Consequently, the altered distribution of roots and water in the soil and weathered bedrock may have changed the mechanical and chemical weathering in watersheds converted to grass compared to those remaining under chaparral (Canadell et al., 1996; Drever and Finley, 1993).

The different rooting habits of the plants are reflected in differences in A-horizon soil color, carbon distribution and thickness between the two vegetation types (Tables 2 and 3). Leaf and stem litter are the primary source of organic matter in chaparral soils, so carbon concentrations are highest at the surface in the thin A-horizon (Lossaint, 1973). Accumulation of organic matter is a dominant process in grassland soils, and conversion to grassland increases humus content throughout the upper part of the soil (Buol et al., 1980; Lepilin, 1989). There is no evidence of a difference in bioturbation between areas of chaparral and grass; consequently, the dispersal of carbon throughout the upper 6 cm of soil and darker colors under grass are probably a result of root decay and subsequent additions of organic matter to the soil. Organic matter content affects water retention and bulk density (Brady, 1990; Martinez-Fernandez et al., 1995; Patgiri et al., 1993; Rajkai et al., 1996), both of which changed as a result of the SDEF vegetation conversion.

Thicker A-horizons indicate that organic matter is dispersed through a larger portion of the soil under grass relative to chaparral, including soil material that was part of B-horizons prior to the conversion. What are now grass AB-horizons were originally chaparral B-horizons. One result is that the mean bulk density for grass A-horizons (including A- and AB-horizons) is higher than that for chaparral A-horizons because the AB-horizon under grass has retained the higher bulk density of the original B-horizon. The transitional horizons themselves are further indication of a change in pedogenic processes as a result of the vegetation conversion. Similar water holding characteristics among grass A-, B- and C-horizons (Table 4) create relatively uniform soil moisture conditions throughout the profile, providing a homogeneous environment for new water moving into the soil.

Infiltration and runoff are examples of hydrologic processes that are structured by interactions with soils and vegetation(Gutierrez et al., 1995; Imeson et al., 1992). Water repellence, one such interaction, prevents rain from immediately entering the soil surface and results in patches of dry soil and local, short-distance runoff. Chaparral brush species produce organic substances that coat soil particles and make the soil water repellent (DeBano and Rice, 1973). Between fires, these hydrophobic substances accumulate in the organic layer and the mineral material immediately below it, resulting in spatially discontinuous water repellence (DeBano, 1981; Imeson et al., 1992; Ritsema et al., 1993). Three of the five chaparral soils exhibited water repellence at the surface (Table 5), and only one of these showed repellence below the surface.

Water repellence in Australian grasslands is associated with fungal hyphae, particularly from basidiomycete fungi (Bond and Harris, 1964). Perennial veldt grass has been associated with very severe water repellence (King, 1981). Each of the grass soils analyzed in this study exhibited water repellence (Table 5), and in three of the five, repellence extended below the surface horizon. These data suggest that the spatial variability in water repellence changed as a result of the vegetation conversion, and that repellence now extends deeper.

Water repellence does not seem to inhibit the infiltration capacity of soils in either vegetation environment (the surface material was left intact during infiltration measurements). Ponded infiltration rates under both vegetation types exceed recorded rainfall rates published for the SDEF (Reimann and Hamilton, 1959), decreasing the potential for Hortonian (infiltration exceedence) overland flow in either vegetation environment. However, ponded infiltration measurement does not reveal how water moves into the soil during natural precipitation events. Examination of the wetting front after the first large rainfall of the year showed that storm water is distributed differently under the two vegetation types (Fig. 6). Under chaparral, the relatively large range in water content (18% under chaparral vs. 11% under grass) suggests preferential flow. The chaparral wetting front does not solely follow the bedrock structure, and there is evidence of preferential flow around a small burrow as well as away from many larger roots (Fig. 6a). Under grass, the lower variability in water content, regardless of the presence of burrows, and deeper wetting front indicate a more uniform dispersal of water into and within the regolith relative to chaparral areas. This type of laterally homogeneous water movement into the soil, caused by the high frequency of plants, uniform canopy and root distribution, and similar soil properties between A- and B-horizons has been observed in other areas of grass vegetation (Himo et al., 1987; Lepilin, 1989). The differences between A- and B-horizons of chaparral soils with respect to bulk density and water retention are larger than those under grass. This type of layered soil can lead to preferential flow (Jury et al., 1991), as was observed at the chaparral site.

5. Conclusions

Veldt grass was introduced four decades ago in the SDEF as part of fire-rehabilitation and hydrology research. Sufficient time has elapsed for the difference in vegetation to alter soil properties (A-horizon thickness and carbon distribution) and associated hydrologic conditions (bulk density, hydrophobicity and the natural wetting front) in the SDEF watersheds. Accumulation of organic matter around the dense, fibrous, grass roots resulted in transitional AB-horizons that provide a gradual transition from the surface to the subsoil. Transitional horizons are absent from chaparral watersheds, where there is significant contrast between the hydrologic characteristics (e.g., water retention and bulk density) of the thin A-horizon and the subsoil. Soil morphologic changes in converted areas originate adjacent to grass tussocks and spread downward and laterally, so the significantly higher frequency of grass plants has caused concurrent transformation of much of the grass watershed.

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